# Late-phase acceleration of energetic ions in corotating interaction regions

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**Abstract**. We report on new high-sensitivity measurements from the WIND spacecraft of the spatial distributions of 30 keV/amu to 10 MeV/amu ions from corotating interaction regions (CIRs) that extend far beyond the confines of the parent high-speed solar-wind stream. Not only do late-phase MeV ions persist far into the declining solar wind, but they also show a continual gain in energy, even after sector boundary passage, until the next small increase in solar wind speed occurs. These ions are accelerated in the distant heliosphere as the reverse shock from the CIR propagates completely across the rarefaction region produced by the declining solar wind, growing in acceleration efficiency as it propagates. Energetic ions from a single CIR event are seen for a period of 17 days and ~225$^{o}$ in solar longitude. The observed energy spectra can be fit to the theory of *Fisk and Lee* [1980] only if shock compression increases with time so that the spectra harden significantly.

## Introduction

Corotating interaction regions (CIRs) are formed when high-speed solar wind streams, emerging from solar coronal holes, overtake low-speed solar wind emitted earlier during the solar rotation. The strongest interaction occurs beyond the orbit of Earth where shock waves form: a forward shock propagates outward into the slow wind and a reverse shock propagates inward into the fast solar-wind stream. Ions can be accelerated to MeV energies at both of these shocks, although the strongest acceleration occurs at the reverse shock where MeV ions then propagate sunward toward Earth through the high-speed stream. CIRs are large stable spatial structures that can persist for many solar rotations. The first evidence of these structures came from the recurrent streams of energetic ions seen on successive 27-day solar rotations. These ions were subsequently associated with high-speed solar-wind streams and CIRs [*McDonald et al.* 1975; *Barnes and Simpson* 1976; *Intriligator and Siscoe* 1994]. Anisotropies in the arrival direction of ions, measured in the rest frame of the solar wind, confirm that the ions are streaming toward the sun along the magnetic field [see *e.g. Richardson et al. 1993*]. *Fisk and Lee* [1980] presented a theory that includes the acceleration of ions at the shock, transport to 1 AU and the effects of adiabatic cooling. The energetic ions from CIRs are also known to have very characteristic element abundances that distinguish them from other populations of energetic particles [see *Reames et al.* 1991; *Reames* 1995; *Richardson et al.* 1993; *Mason et al.* 1997].

In previous experiments, energetic particles from the reverse shock have been observed at 1 AU mainly on magnetic field lines that connect to that shock and lie entirely in that portion of the high-speed stream that can overtake low-speed wind. *Fisk and Lee* [1980] compare their theory with observations that are only 1 AU upstream of the shock. Generally it has not been possible to follow the spectral evolution throughout the entire sector containing high- and low-speed wind while the shock propagates several AU away from the observer.

The sensitive particle telescopes aboard the *WIND* spacecraft give us the power to measure intensities of MeV ions that are ~100 times lower than those seen by the previous generation of instruments on *IMP 8*, *ISEE 3*, *Pioneer 9* and *10*, and *Voyager 1* and 2. Thus, we are able to explore particle populations once dismissed as low-intensity "background." We find clear evidence of energetic ions from CIR shocks over a vast spatial region corresponding to far more than half a solar rotation.

## Instrumentation

The Energetic Particles, Acceleration, Composition and Transport (EPACT) experiment aboard the *WIND* spacecraft, launched 1994 November 1, has been described by *von Rosenvinge et al.* [1995]. Within EPACT, the Supra-Thermal Energetic Particle (STEP) system measures ion time-of-flight *vs.* energy to resolve elements and isotopes of He in the ~20 keV/amu to ~1 MeV/amu region, while the Low Energy Matrix Telescope (LEMT) system uses *dE/dx vs. E* techniques to resolve these same species from ~2 to ~20 MeV/amu. Geometry factors for the STEP and LEMT systems are 0.8 and 51 cm$^{2}$ sr, respectively. The element and isotope resolution of these two telescope systems has been presented by *Reames et al.* [1997].

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## Time evolution

Figure 1 shows He-ion intensities *vs.* time for one 27-day solar rotation period during the declining phase of the solar cycle in 1995. We show He ions rather than protons only because our energy coverage is more complete for He. The middle panel in the figure shows the solar wind speed while the upper panel shows the azimuth angle of the magnetic field in order to exhibit the magnetic sector structure. A small high-speed solar wind stream begins on May 23 and a larger one on May 30. The CIR and shocks are not well defined at 1 AU, nevertheless, ion increases are seen near the onset of each stream.

A rise in low-energy ion intensities on May 29, *before* onset of the large stream, corresponds to ions from the forward shock. After crossing the stream interface, ions are seen from the reverse shock in the large high-speed stream. As the magnetic connection point moves further out along the reverse shock with time, low-energy ions appear first from the young weak shock. Then, higher-energy ion intensities increase as the shock strengthens while the low-energy ion intensities decrease from the effect of the greater transport distance. This behavior is in qualitative agreement with expectations from the theory of *Fisk and Lee* [1980]. Near the sun, the high- and low-speed streams propagate nearly parallel to each other. Farther out, the high-speed stream begins encounters the low-speed wind "head-on" and the shock becomes increasingly strong.

By June 3, low-energy ion intensities have declined as we reach the end of the high-speed region and the solar wind speed begins to decline. However, the decline in solar-wind speed is accompanied by *increasing* ion intensities, especially at the highest energies, where a measurable increase at ~5 MeV/amu is now seen for the first time. These high-energy intensities continue to rise until June 9, almost a day after the June 8 sector passage. There the ions at <1 MeV/amu fall to background levels and those at >1 MeV/amu decrease in intensity by an order of magnitude or more, coincident with a small, 80 km/s increase in the solar wind speed. Perhaps this speed increase begins to form a new interaction region with enough turbulence to impede the transport of particles or interfere with the distant shock. Beyond this point, the MeV ions can be seen to persist, with declining intensity, up until the *next* sector boundary crossing on June 14. By that time, ions from this CIR event have been visible for about 17 days or 226° of longitude, completely spanning two magnetic sec-

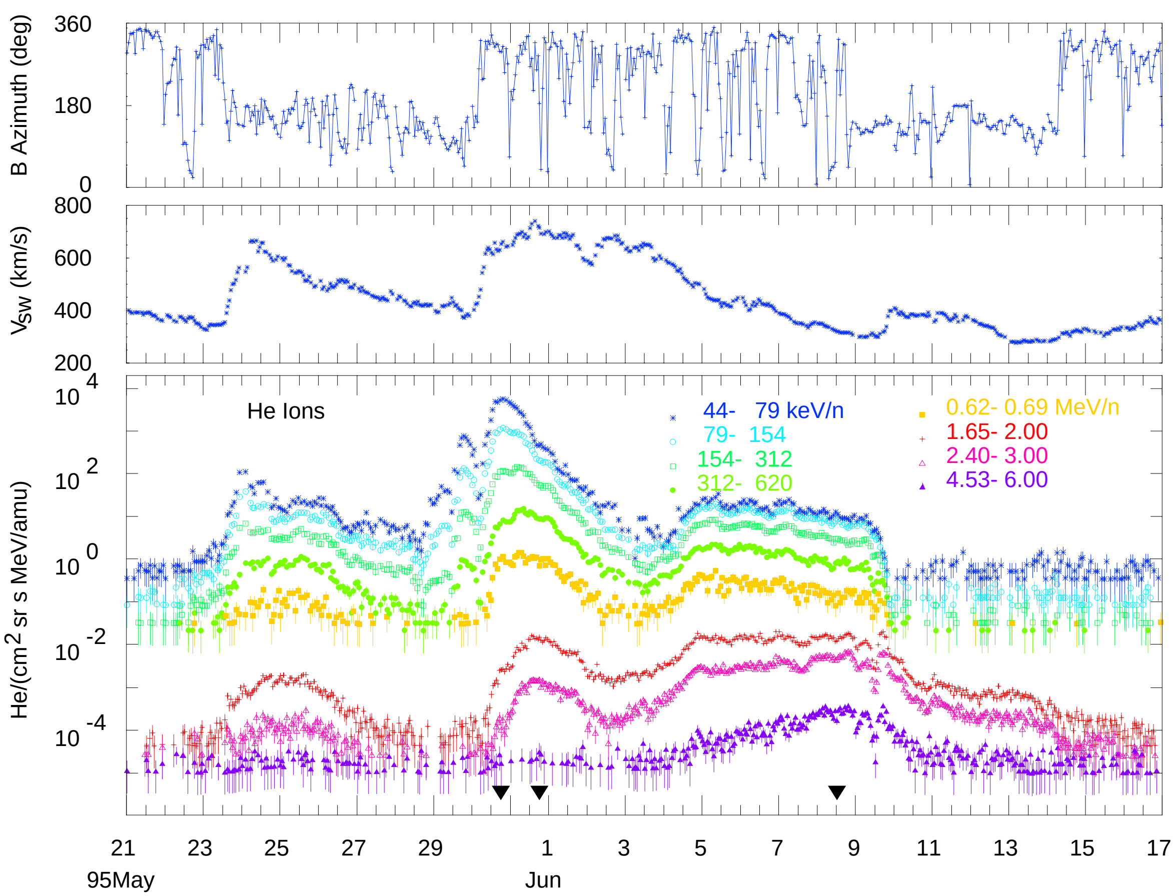


**Figure 1.** Time profiles of energetic He ions of the energies listed are plotted for one 27-day solar rotation in the lower panel. Solar wind speed and magnetic azimuth angle (to indicate sector structure) are shown in the upper two panels. A plateau of late-phase ions is clearly seen in the region of slow solar wind on June 5 - 9, extending beyond sector boundary passage.

tors.

Space does not permit us to show the evolution of this stream on other solar rotations or the late-phase ions from other CIRs; these data will be presented in a subsequent paper. However, we remark that the main stream discussed here is clearly seen on at least two prior solar rotations, with a plateau of MeV late-phase ions extending to the following sector boundary, albeit with lower intensity. Furthermore, the small stream beginning on May 23 in Figure 1 develops a pronounced late-phase plateau on the next solar rotation, with intensities rising up to the sector boundary. Note that the main (May 30) stream exists in a magnetic sector with the field directed toward the Sun along the Parker spiral, while the small (May 23) stream is in an "away" sector. In all these other cases, the late-phase ions do not extend as far beyond the first following sector boundary as they do in the June 9 period shown in Figure 1.

## Spectra

In Figure 2 we show energy spectra taken for 3 time periods during the main CIR event, May 30 1200- 2400 UT, May 31 1200-2400 UT and June 8 0000-2400 UT. Times at the center of each interval are listed in Figure 2 and noted along the abscissa in Figure 1. These 3 periods represent peak

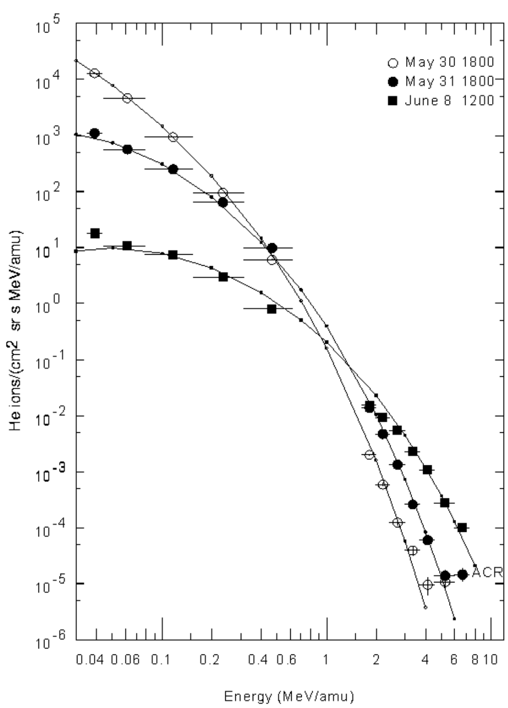


**Figure 2.** Energy spectra of ions are shown for the times indicated (see text). Fitted curves based on the theory of *Fisk and Lee* [1980] are shown through the observed points. Continual hardening of the source spectra is required to obtain the fits.

intensity at the lowest energy, the initial peak intensity near ~2 MeV/amu, and the late phase peak intensity of ions of ~ 5 MeV/amu, respectively. The spectra in the 2 earlier periods show a flattening in intensity at ~$10^{-5}$ particles (cm$^2$ sr s MeV/amu)$^{-1}$ where the anomalous cosmic-ray (ACR) component begins to dominate [see *Reames, Barbier and von Rosenvinge* 1997].

Curves through the spectra in Figure 2 are calculated from the asymptotic expansion in particle speed given by Equation 6 in the theory of *Fisk and Lee* [1980]. To obtain agreement, we used the observed solar wind speed at each time, we treated $\beta$ and $r_s$ in the theory as adjustable parameters, and we normalized each spectrum to the observations. For the shock distance $r_s$, we used 1.2, 2, and 4 AU, respectively, and for the parameter $\beta$, which is the inverse of the shock compression ratio, we used values 0.40, 0.36, and 0.20 for the 3 spectra. In all cases we used a parallel scattering mean free path corresponding to 0.2 AU at 1 AU. A shock compression ratio that increases with time is expected; however, the large value found late in the event is discussed in the next section.

For a fixed diffusion coefficient, the theoretical spectra roll over sharply at low-energies when large values of $r_s$ are used, in disagreement with the observations. Larger values of $r_s$ can be accommodated if the scattering mean free path is increased, but harder source spectra are then needed as well. These alternatives suggest that the precise values of the parameters we used should not be taken too literally.

## Discussion

Models of CIR evolution such as that shown by *Hundhausen and Gosling* [1976] show that the reverse shocks propagate well into a declining solar-wind speed profile out to 4 AU. It is quite possible that the shock can propagate completely across the rarefaction region under suitable conditions [*Gosling*, 1997, private communication]. For the event we have studied, the extreme hardening of the spectra of the late-phase ions suggests that this shock actually strengthens considerably as it propagates into the slowing solar wind.

The parameters $r_s$ that we determined from fitting the theory of *Fisk and Lee* [1980] should be considered as being relative to the diffusion coefficient; if we decrease the amount of scattering, larger values of $r_s$ would be necessary. The parameter $\beta$ from the theory is actually the inverse of the shock compression ratio, and the value of 0.20 late in the event implies a compression ratio of 5, larger than the Rankine-Hugoniot limiting value of 4. Within the asymptotic Fisk-Lee formula, we are unable to fit the observations with a smaller value of the compression ratio. However, if we assume that the diffusion coefficient near the shock is increased relative to that far upstream, then the shock compression ratio can be reduced by the same factor as the scattering near the shock is increased.

We could also fit the data using a smaller shock compression ratio if the solar wind speed at the shock were higher. There are physical processes might act to make the field lines in the slow solar wind connect to a reverse shock that is still in higher-speed regions. For example, the eastward drift of the photospheric footpoints of the open field lines, described by *Wang and Sheeley* [1993], might move field lines from fast to slow solar wind over the time scale of a solar rotation. The period of declining solar wind speed actually maps to a small longitude interval on the sun, so the amount of required field-line migration would be small. This mechanism was used by *Fisk* [1996] to explain the presence of energetic particles from CIRs observed at extremely high solar latitudes. However, in our event, the constancy of energetic ion intensities across the June 8 sector boundary would be difficult to explain with this mechanism. It seems more likely that the shock itself crossed this boundary and continued acceleration. Field line migration might explain other cases where ion intensities are lower and terminate at the following sector boundary.

Despite the limitations mentioned above, it is still impressive that the asymptotic expansion published 17 years ago by *Fisk and Lee* [1980] fits the new observations over such large intervals of both particle energy and solar longitude.

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